Gaseous Non-Premixed Flame Research
Planned for the International Space Station

Spring Technical Meeting of the
Central States Section of
The Combustion Institute
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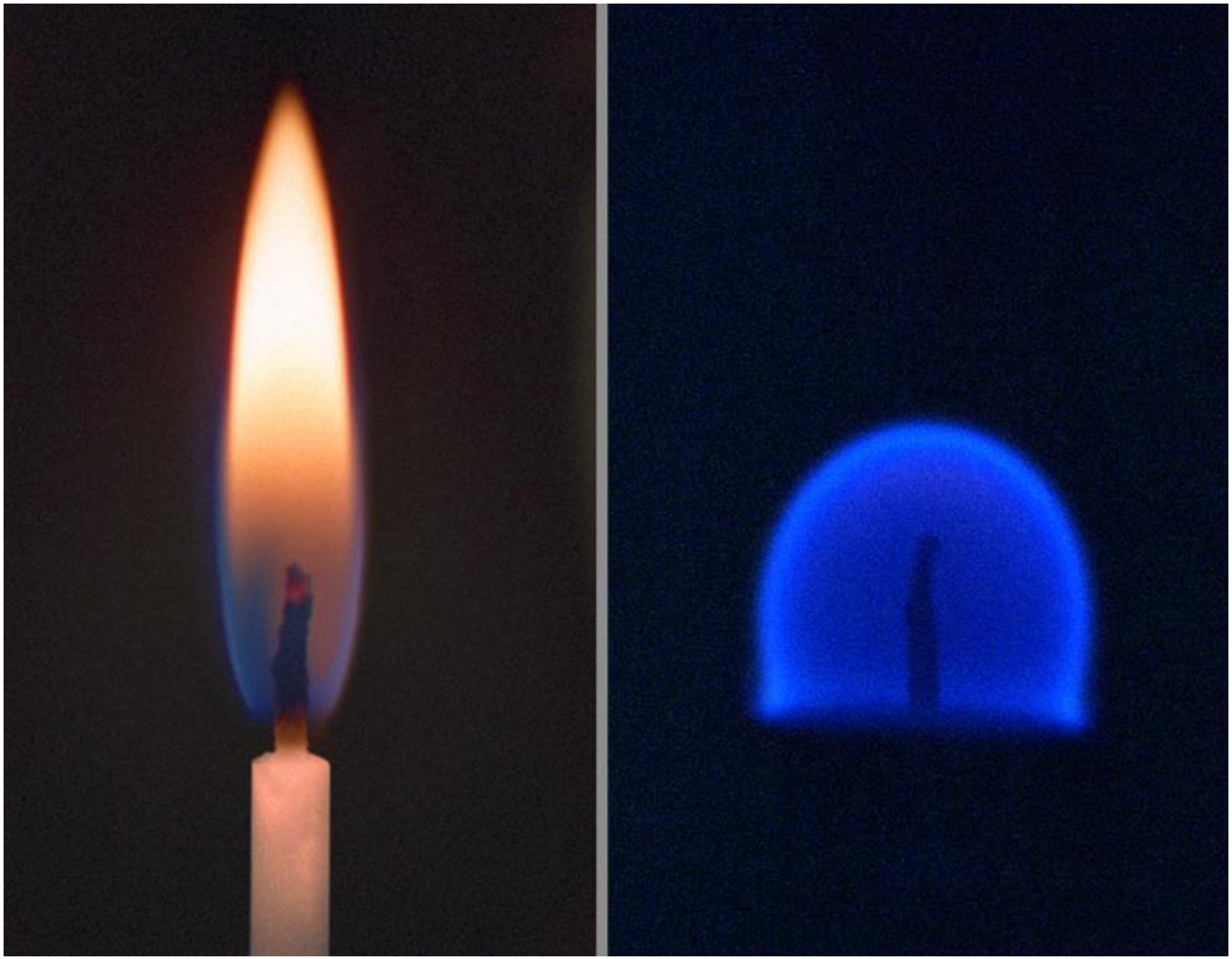
Outline

- **Background**
  - Why microgravity?
  - Gaseous non-premixed flames in space
- **ACME**
  - Science
  - Hardware
  - Status
- **Questions**

Why Microgravity?



- Effective elimination of buoyancy and buoyancy-induced flicker
- Spherical flames
- Momentum-dominated flames at low velocities
- Increased length scales
- Longer residence times - good for studies of soot
- Stronger flame sensitivity to atmosphere
- Studies of limit and stability behavior, where chemical kinetics dominate
- Spacecraft fire safety

Gaseous Non-premixed Flames in Space

3 space shuttle and 2 ISS experiments thus far

Space Shuttle

LSP: Laminar Soot Processes
- PI: G.M. Faeth (U. Michigan)
- Combustion Module
- STS-83 and STS-94 (1997), STS-107 (2003)

TGDF: Turbulent Gas-jet Diffusion Flames
- PI: M.Y. Bahadori (SAIC)
- Get Away Special Canister (GAS can)
- STS-87 (1997)

ELF: Enclosed Laminar Flames
- PI: L.-D. Chen (U. Iowa)
- Middeck Glovebox (MGBX)
- STS-87 (1997)

ISS

SPICE: Smoke Point In Coflow Experiment
- PI: D.L. Urban (NASA Glenn) - *initially G.M. Faeth*
- Microgravity Science Glovebox (MSG)
- ISS Expeditions 18-19, 30 (2009, 2012)

LSP follow-on

SLICE: Structure & Liftoff In Combustion Experiment
- PI: M.B. Long (Yale U.)
- Microgravity Science Glovebox (MSG)
- ISS Expedition 30 (2012)

ACME precursor

Roger Crouch with CM-1 on STS-83 (top), Michael Barratt with SPICE (bottom)

Advanced Combustion
via Microgravity Experiments

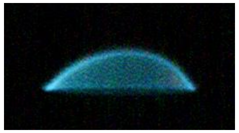
- Conduct **5+ distinct experiments** using a **single modular insert** for the Combustion Integrated Rack (CIR) on the ISS
  - *The only existing CIR insert, MDCA, is for the FLEX droplet combustion experiments, which have been collectively operating on ISS since 2009*

Koichi Wakata with MDCA in CIR (left), ISS (right)

5 Current ACME Experiments

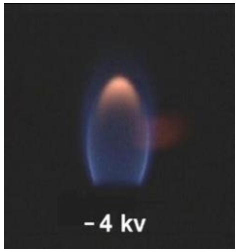
11 Investigators and 7 Universities (+ NASA Glenn)

- **BRE**
  - **Burning Rate Emulator**
  - PIs: James G. Quintiere, Peter B. Sunderland (both U. Maryland)



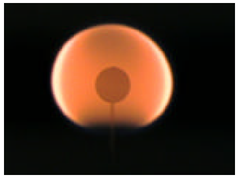
- **CLD Flame**
  - **Coflow Laminar Diffusion Flame**
  - PIs: Marshall Long, Mitchell Smooke (both Yale U.)

- **E-FIELD Flames**
  - **Electric-Field Effects on Laminar Diffusion Flames**
  - PI: Derek Dunn-Rankin (UC Irvine)



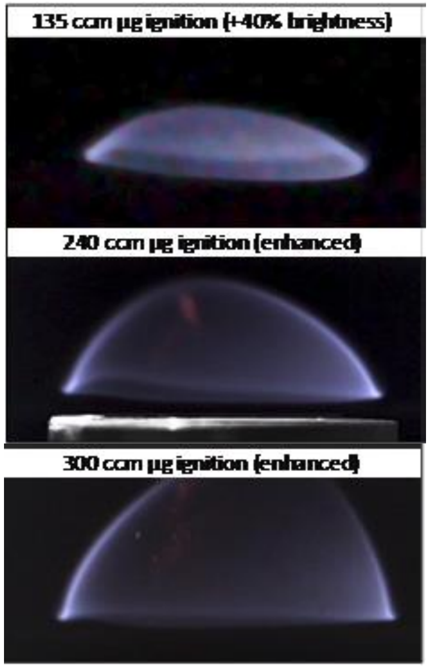
- **Flame Design** ***- a novel approach to clean, efficient diffusion flames***
  - PIs: Richard L. Axelbaum (Washington U. in St. Louis), Beei-Huan Chao (U. Hawaii), Peter B. Sunderland (U. Maryland), David L. Urban (NASA Glenn)

- **s-Flame**
  - **Structure and Response of Spherical Diffusion Flames**
  - PIs: C.K. Law (Princeton U.), Stephen D. Tse (Rutgers U.), Kurt R. Sacksteder (NASA Glenn)



BRE

- **Burning Rate Emulator**
  - **Jim Quintiere** & Peter Sunderland (both U. Maryland)
- **Concept**
  - Flat-plate burner with gaseous fuel flow simulating the vaporization and combustion of condensed fuels
  - Heat flux to the burner is measured, where the flux vaporizes condensed-phase fuels
    - Fuels to be simulated include paper, plastic, alcohols
- **Goals**
  - Quantify the burning and extinction behavior of condensed fuels in microgravity
  - Quantify the effects of increased O2 concentrations, e.g., for exploration atmospheres, on µg combustion.
- **Why?**
  - Spacecraft fire prevention through improved assessment for materials selection (currently based on 1g testing, where flames can exist in µg and not in 1g)



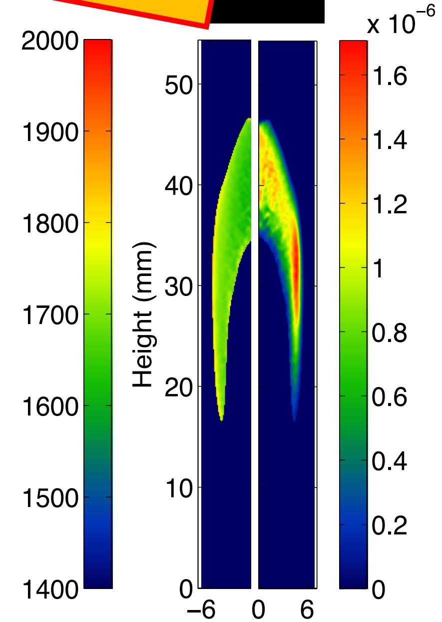
50-mm diam. burner
C2H4 (various flows)
in air at 1 atm
µg flame
near end of 5.18 s drop

CLD Flame

- **Coflow Laminar Diffusion Flame**
  - **Marshall B. Long** & Mitchell D. Smooke (both Yale U.)
- **Concept**
  - Lifted coflow (2D) flame, so little/no heat loss to burner
    - enabling improved modeling of the flame
- **Goals**
  - Generation of modified kinetic mechanisms for hydrocarbon fuels that are able to model effectively diffusion flame structure under a larger parameter range than existing mechanisms.
  - Development of submodels for soot formation that are capable of predicting both high and low soot loading levels in hydrocarbon flames of various fuels.
- **Why?**
  - Improved design capability through validation of combustion models over wider parameter range

Attached 100% CH4 flame on a 1.6-mm ID burner tube, with soot temperature, soot volume fraction below.

SLICE results



E-FIELD Flames

- **Electric-Field Effects on Laminar Diffusion Flames**
  - **Derek Dunn-Rankin** (UC Irvine)
- **Concept**
  - Gas-jet or coflow (2D) flame with high-voltage mesh (up to ±10 kV) electrode above (downstream of) burner
- **Goal**
  - Understand chemi-ionization behavior and the resulting ion driven winds sufficiently well so that electrical properties of flames can be used to **characterize** (by monitoring ion current) and **control** them (via direct chemical or local convective influences).
- **Why?**
  - Advanced control capability enabling improved combustion performance

1g, 0 kV, gas-jet

0g, -0.6 kV, gas-jet

0g, 0kv, 24 cm/s coflow

Flame Design

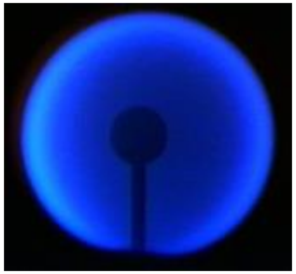
- ***A novel approach to clean, efficient diffusion flames***
  - **Rich Axelbaum** (Washington U., St. Louis), Beei-Huan Chao (U. Hawaii), Peter Sunderland (U. Maryland), David L. Urban (NASA Glenn)
- **Concept**
  - Spherical (1D) flame, normal and inverse flow config.
- **Goals**
  - Evaluate the effects of flame structure on soot inception and flame extinction
  - Obtain a correlation of sooting limits with stoichiometric mixture fraction, *Zst,* and adiabatic temperature, *Tad*
  - Determine the importance of gas-phase oxidation on soot inception for high *Z*st flames
  - Demonstrate the existence of steady spherical flames
  - Identify pseudo-flammability limits for diffusion flames in terms of *Zst* and *Tad*
- **Why?**
  - To reduce soot and NO_x through nitrogen exchange

Normal flames

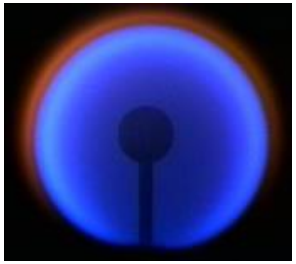
18% C_2H_4 into 27% O_2

18% C_2H_4 Into 28% O_2

Inverse flames



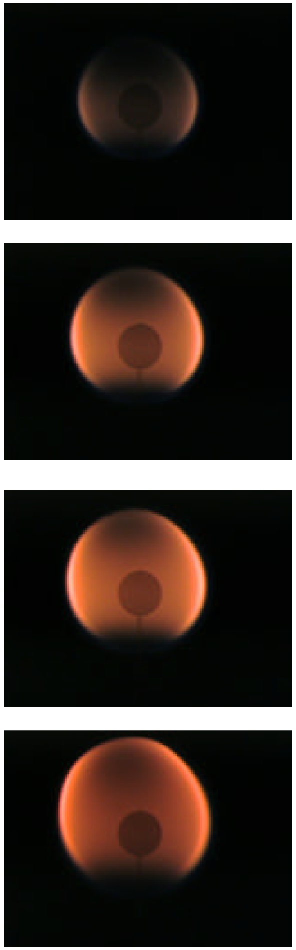
100% O_2 into 12% C_2H_4



100% O_2 into 13% C_2H_4

s-Flame

- **Structure and Response of Spherical Diffusion Flames**
  - **C.K. Law** (Princeton U.), Stephen D. Tse (Rutgers U.), Kurt R. Sacksteder (NASA Glenn)
- **Concept**
  - Spherical (1D) flame stabilized on a porous burner
- **Goals**
  - Use spherical diffusion flames in ISS environment to:
    - obtain experimental data in simple, well-defined flow fields
    - understand various key elemental diffusion flame processes
  - Characterize transient structure, determine extinction limits, and check existence of theoretically predicted pulsating instabilities.
  - Validate and improve accuracy of computational simulation including detailed chemistry and transport
- **Why?**
  - Improvements in the design of practical, high-efficiency, low-emission combustion systems on Earth



flame evolution with time

ACME Approach

- ACME is not a technology demonstration, but is seeking to improve life on Earth via the path below.

ACME

Improved understanding of combustion fundamentals

↓

Improved numerical models of combustion processes

↓

from ACME

Improved design tools

↓

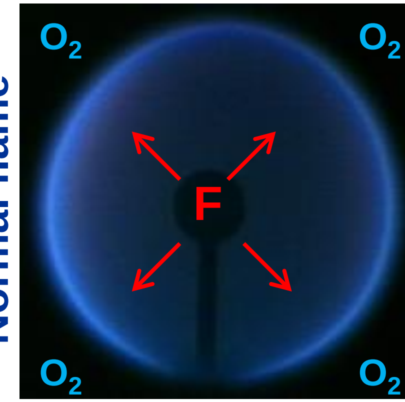
Improved practical combustion devices

Numerical prediction of flame structure **[Yale U.]**

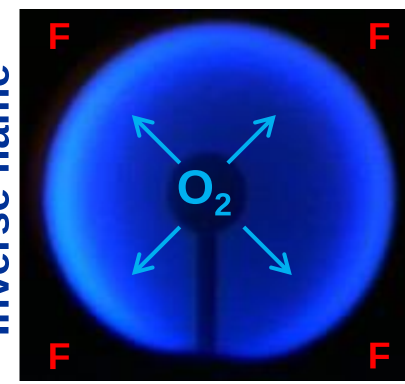
Similarities of Current Experiments

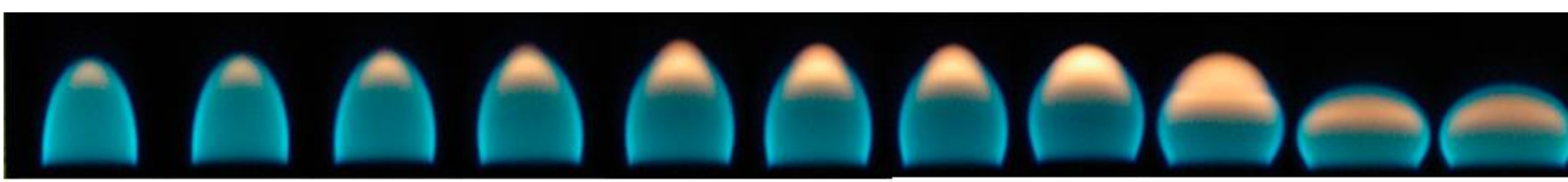
- **Gaseous flame**
  - fuel is a gas, e.g., methane and ethylene
- **Non-premixed (i.e., diffusion), flame**
  - fuel and oxidizer (e.g., air) are on opposite sides of the reaction sheet
  - ***but premixed flames can be studied with ACME***
- **Laminar flame**
  - flow is smooth and not turbulent (i.e., w/o vortices)
  - ***but turbulent flames can be studied with ACME***
- **1D or 2D flame**
  - ***but 3D flames can be studied with ACME***

Normal flame



Inverse flame

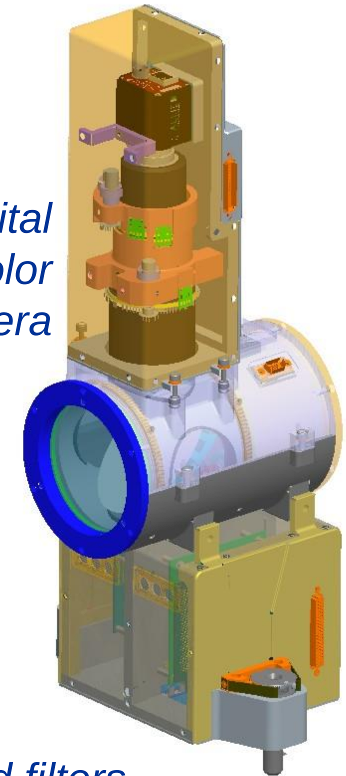




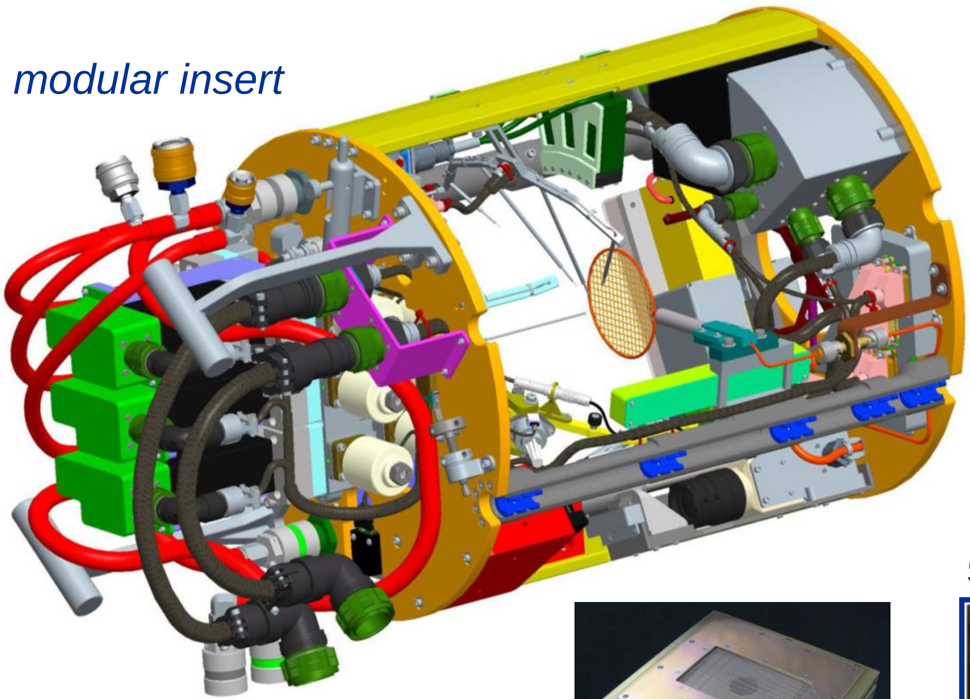
-2.25kV/cm | -2kV/cm | -1.5kV/cm | -1.0kV/cm | -0.5kV/cm | 0kV/cm | 0.75kV/cm | 1kV/cm | 1.17kV/cm | 1.25kV/cm | 1.5kV/cm

ACME Hardware

digital color camera

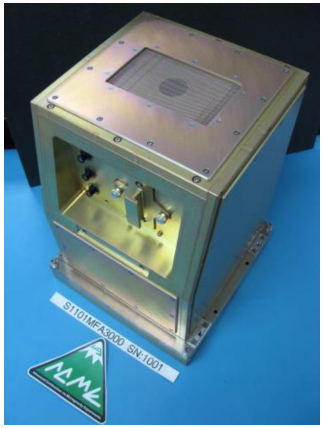


modular insert



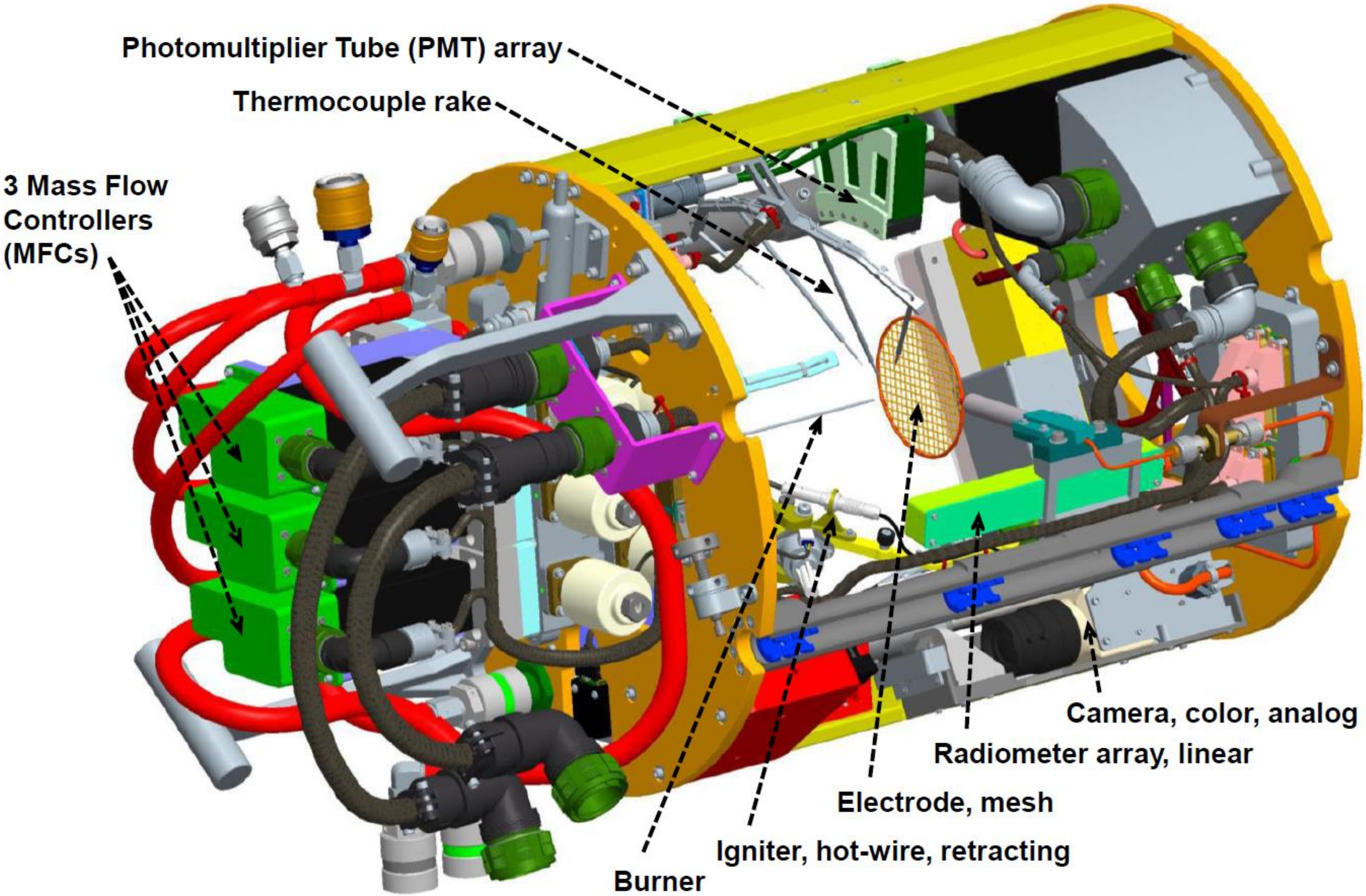
gas bottles and filters

burners



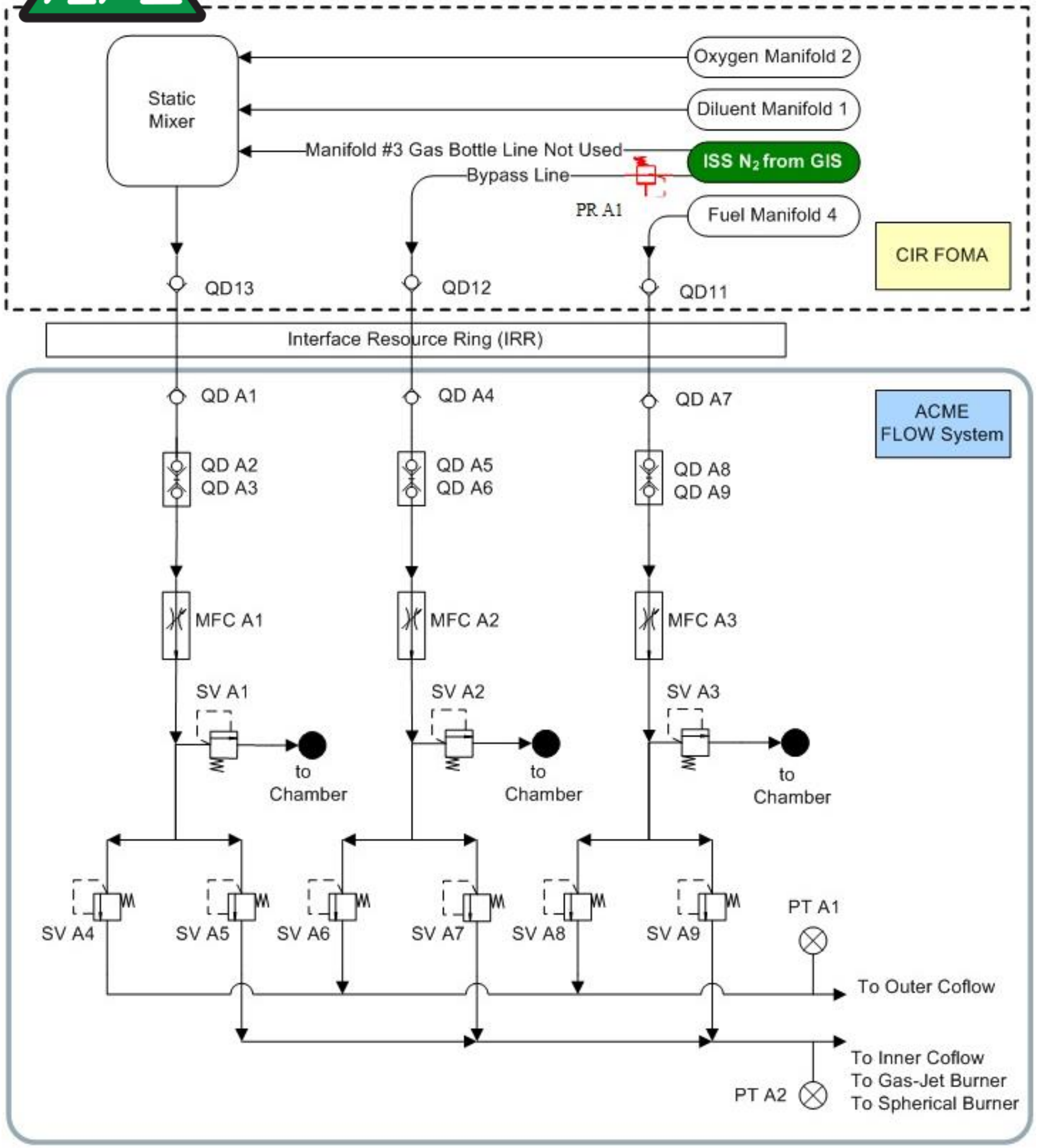
avionics package

ACME Insert

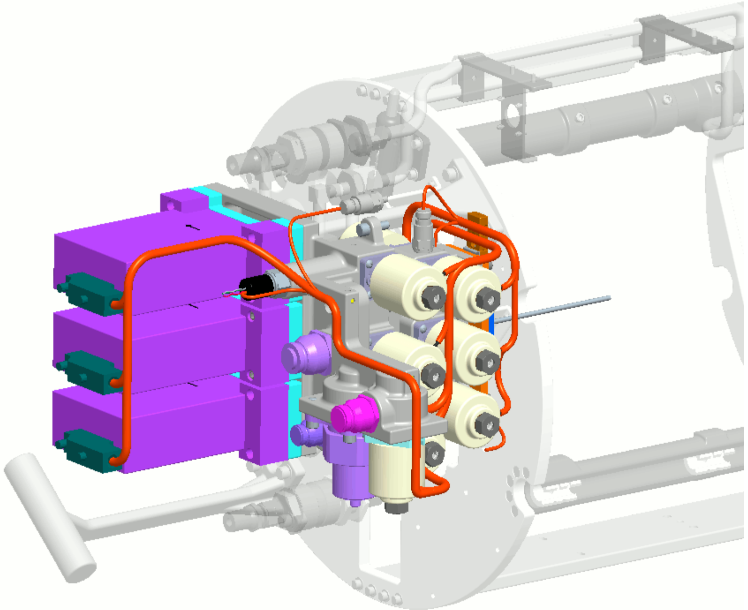


Photomultiplier Tube (PMT) array
Thermocouple rake
3 Mass Flow Controllers (MFCs)
Camera, color, analog
Radiometer array, linear
Electrode, mesh
Igniter, hot-wire, retracting
Burner

Gas Flow System



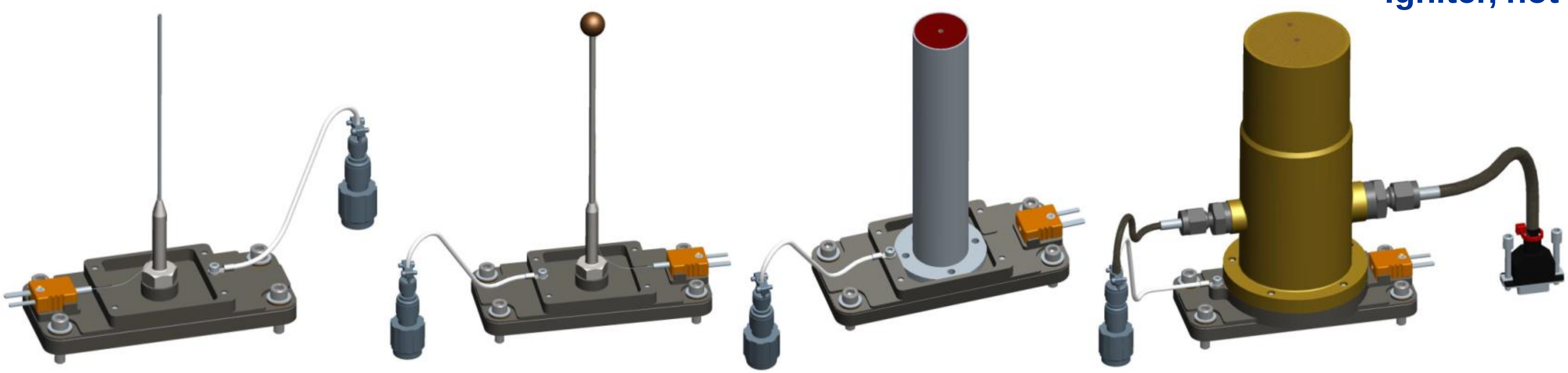
- Delivers 3 gases from CIR to the chamber or burner
  - fuel (2 slpm max, N2 basis)
  - oxygen/inert mix or diluent (e.g., He or CO2)
  - nitrogen (from ISS)
- Mass flow controllers (crew swappable to vary flow ranges)



Burners & Igniter

- **Four types of burners are planned for the first 5 experiments:**
  - **gas-jet burners (7)** 0.4, 0.8, 1.3, 1.6, 2.1, 2.7 and 3.2 mm ID
  - **spherical burners (3)** 0.25, 0.375, 0.5 inch diameter, porous sintered metal
  - **coflow burner (1)** 2.1-mm ID inner tube, 25-mm ID outer tube
  - **BRE burners (2)** 25, 50 mm diameter, porous (w/ 2 heat flux transducers each)
- Thermocouple for surface temperature on most burners
- Burners will generally be electrically isolated
- Hot-wire igniter, retracting, similar to that in use for MDCA
  - Igniter tips are replaceable, e.g., to match the burner type/size

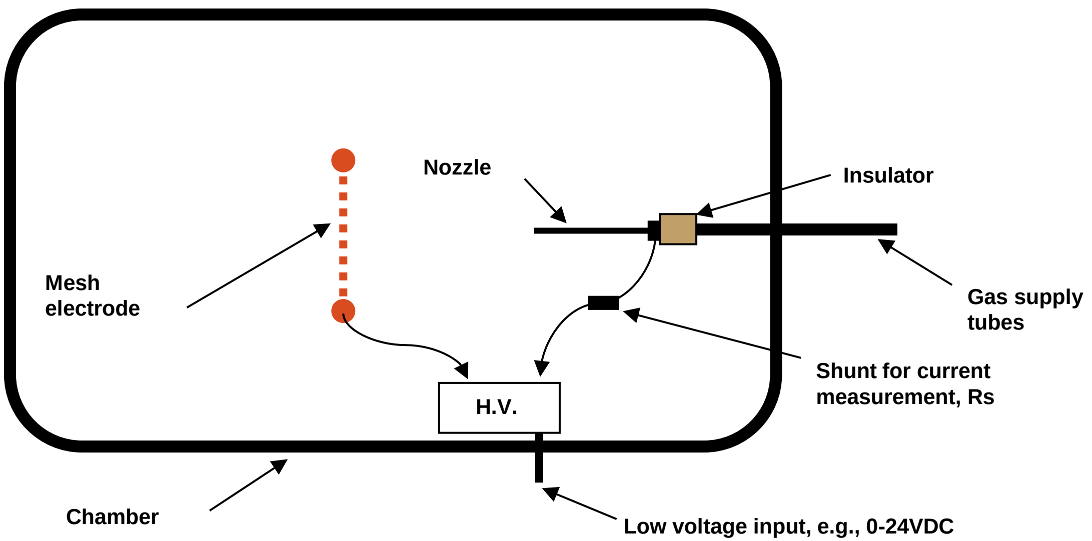
Igniter, hot-wire



Gas-jet, spherical, coflow, and BRE burners (left to right)

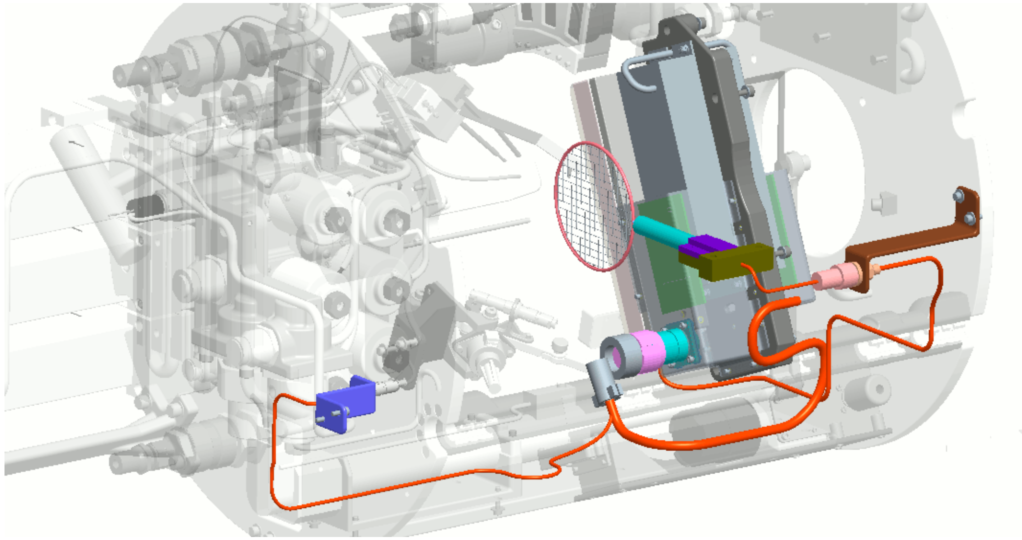
Electric Field

- ±10kV at copper mesh above (i.e., downstream of) isolated burner
- Ion current through flame is determined from Ohm's law (I=V/R) and measurement of the voltage difference across a shunt resistor (in series with the flame)
- copper mesh screen (removable)
- high-voltage source (removable)
- passive electronics (fixed)



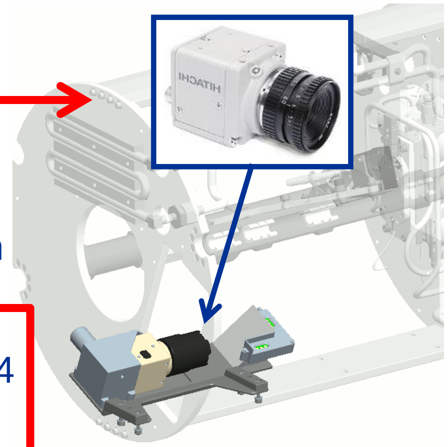
Electrode mesh

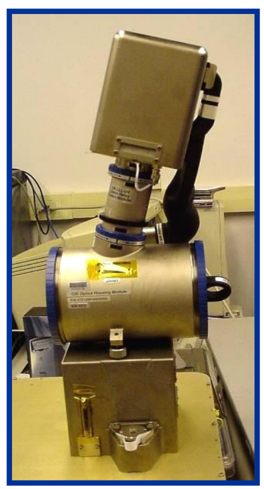
Coflow burner with flame

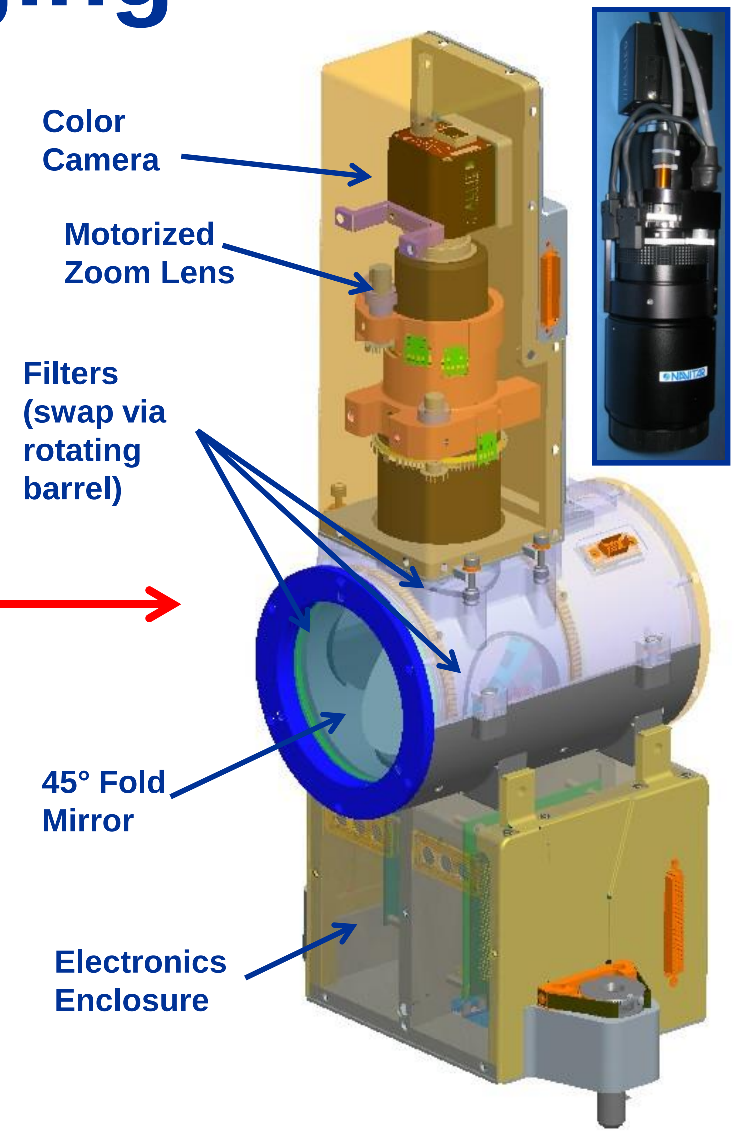


Basic Imaging

- **Color Imaging for Ops**
  - Analog color camera (removable) with 45-degree turning mirror
  - LEDs for optional illumination
- **Color Imaging for Data**
  - Digital GigE color camera, 1.4 megapixel, 12 bit, 30 fps with motorized control of zoom, iris, and focus
  - 3 optional filters including a blue-green BG-7 filter (to balance light intensity for pyrometry), 430 and 450-nm for CH* (incl. soot subtraction)
- **Ultraviolet (UV) Imaging**
  - Existing LLL-UV camera equipped with a 310-nm filter for imaging OH*
  - Field of view (FOV) options: 50-mm and 80-mm diameter

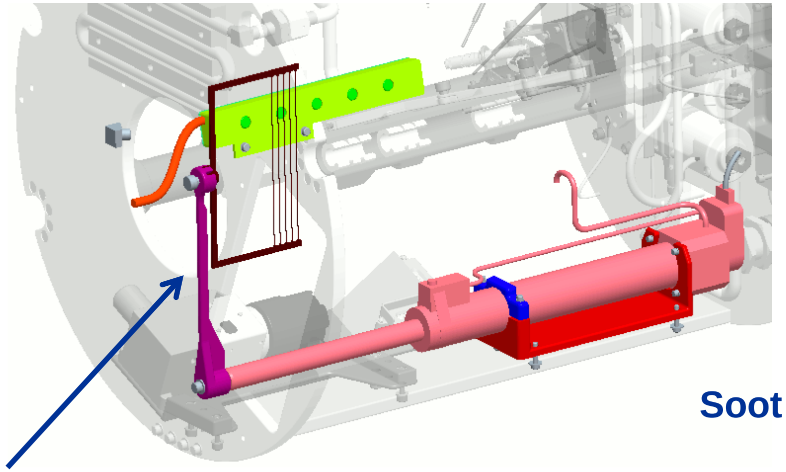


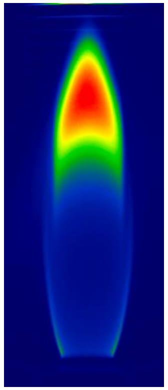




Advanced Imaging

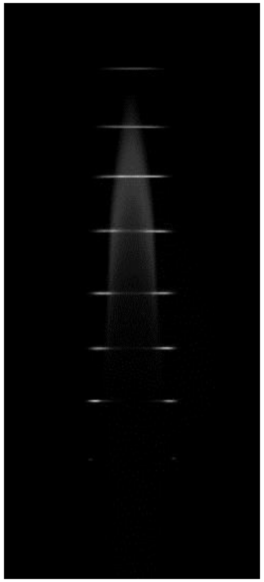
- **Pyrometry for Hot Sooty and Soot-Free Regions**
  - Determine temperature distribution from broadband thermal radiation, where the spectrum is indicative of the temp. using (1) GigE camera and/or (2) HiBMs camera with a liquid-crystal tunable filter.
  - Thin-Filament Pyrometry (TFP) to determine temperature profiles from the broadband thermal radiation. Array of 15-micron oxidized SiC fibers stretched across the flame with motor to allow for scanning or removal of the fibers from the flame. Alternate array includes a Pt wire for absolute light calibration.
  - HiBMs FOV options: 30 and 50-mm dia.
- **Soot Volume Fraction**
  - Via (1) GigE camera or (2) CIR illumination package (using a 653-nm laser diode) and a second HiBMs camera
  - HiBMs FOV options: 30, 50, and 90-mm diameter



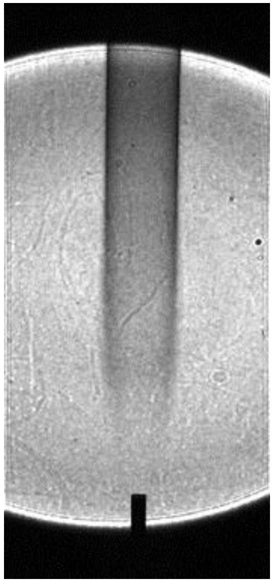


Soot pyrometry

TFP



Soot vol. fraction



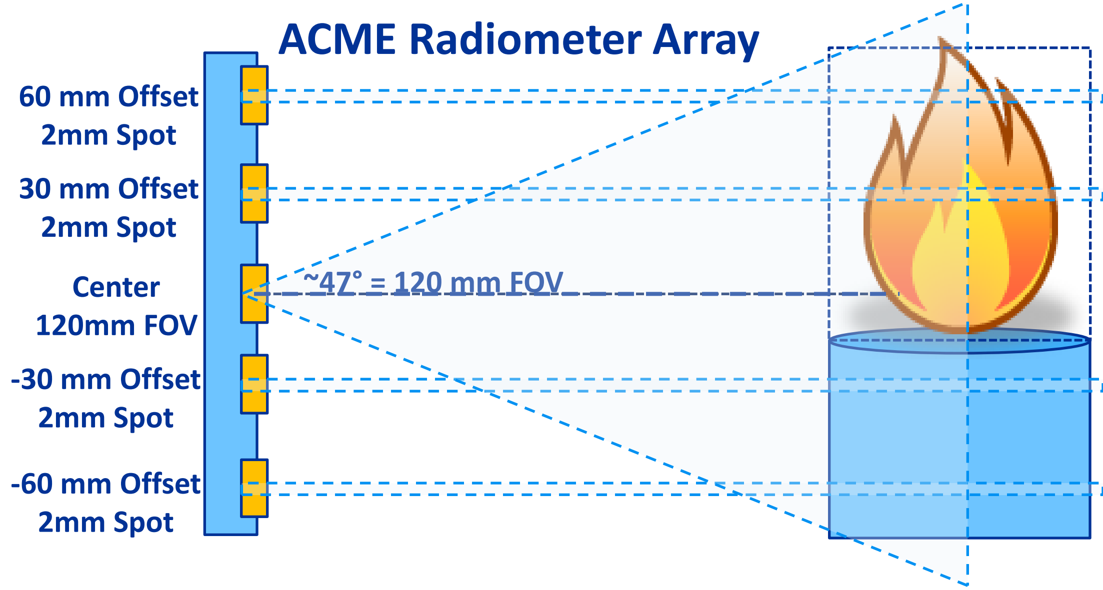
HiBMs camera

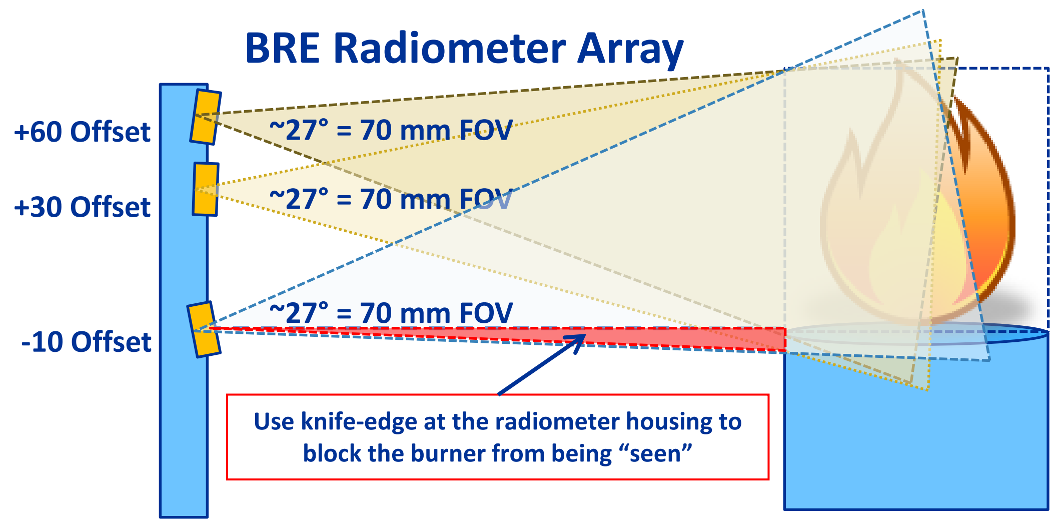
High Bit-depth Multi-spectral (HiBMs)

Emission Measurements

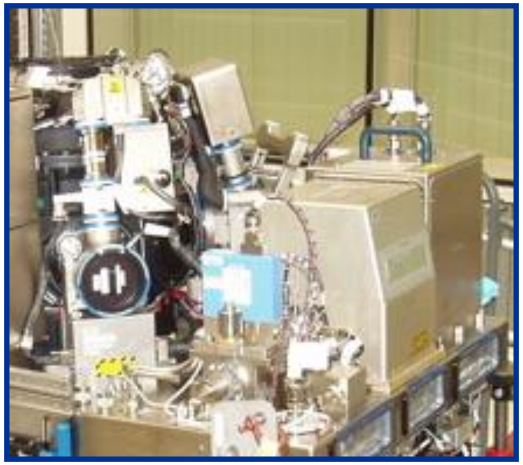
- Photomultiplier Tubes (PMTs)
  - Broadband, OH*, CH* (3 total)

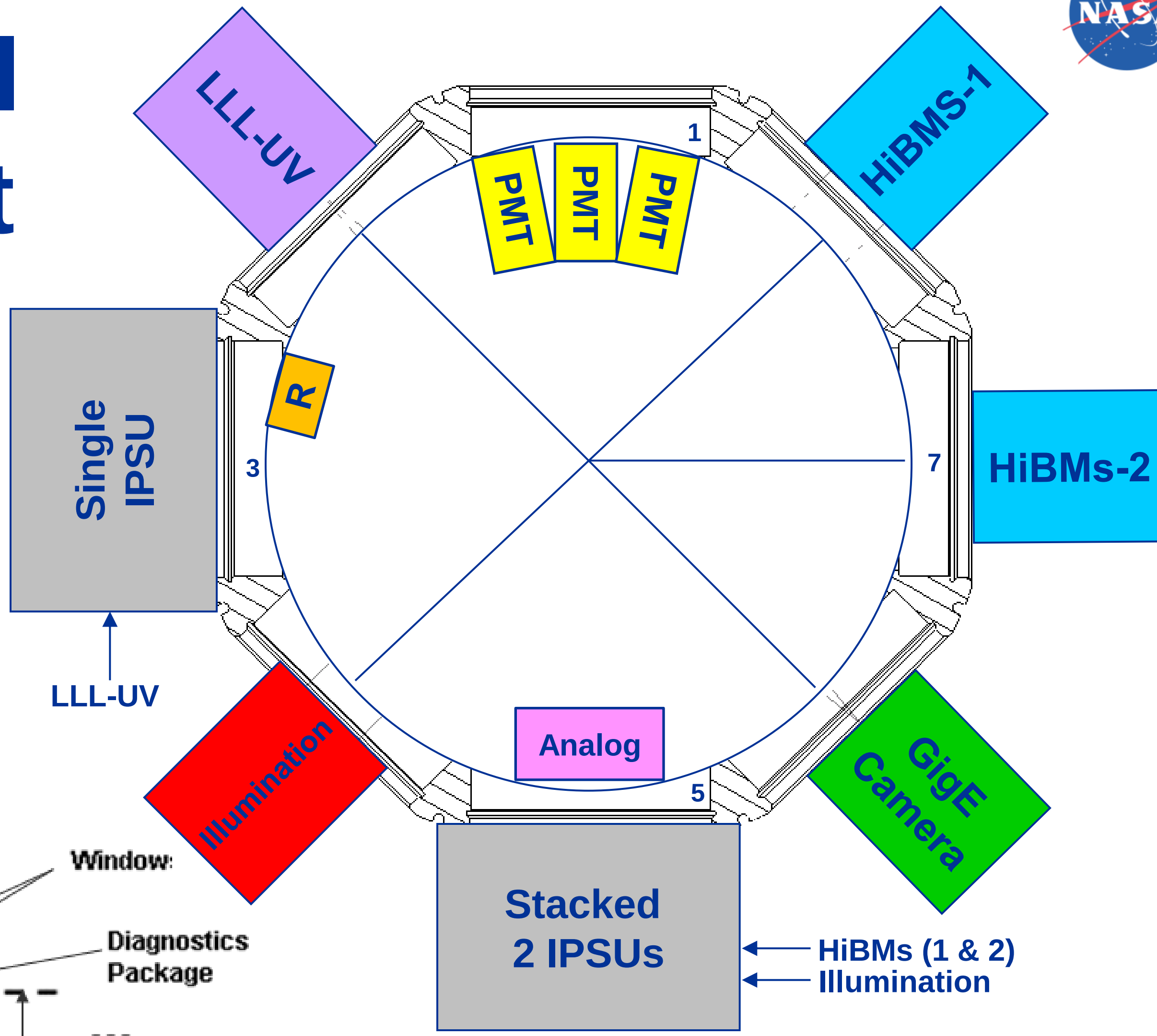
- Radiometers (up to 6 total)
  - Broadband thermal radiation via thermopile detectors
  - Wide and/or narrow angle FOVs
  - One fixed detector
  - An exchangeable array with 2 current options
    - std. array with 5 sensors
    - BRE array with 3 sensors

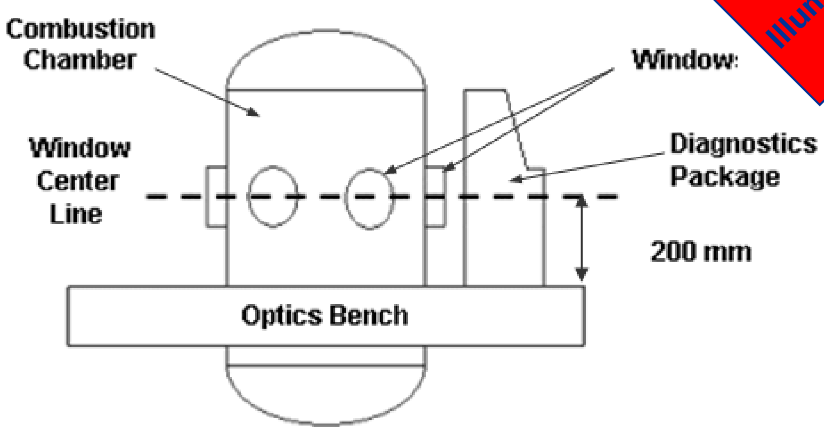




Optical Layout



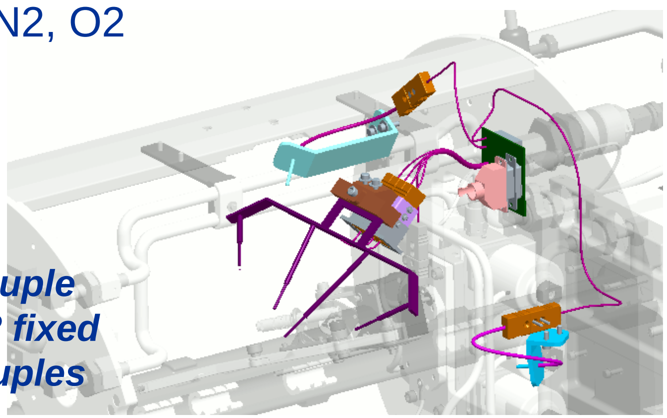




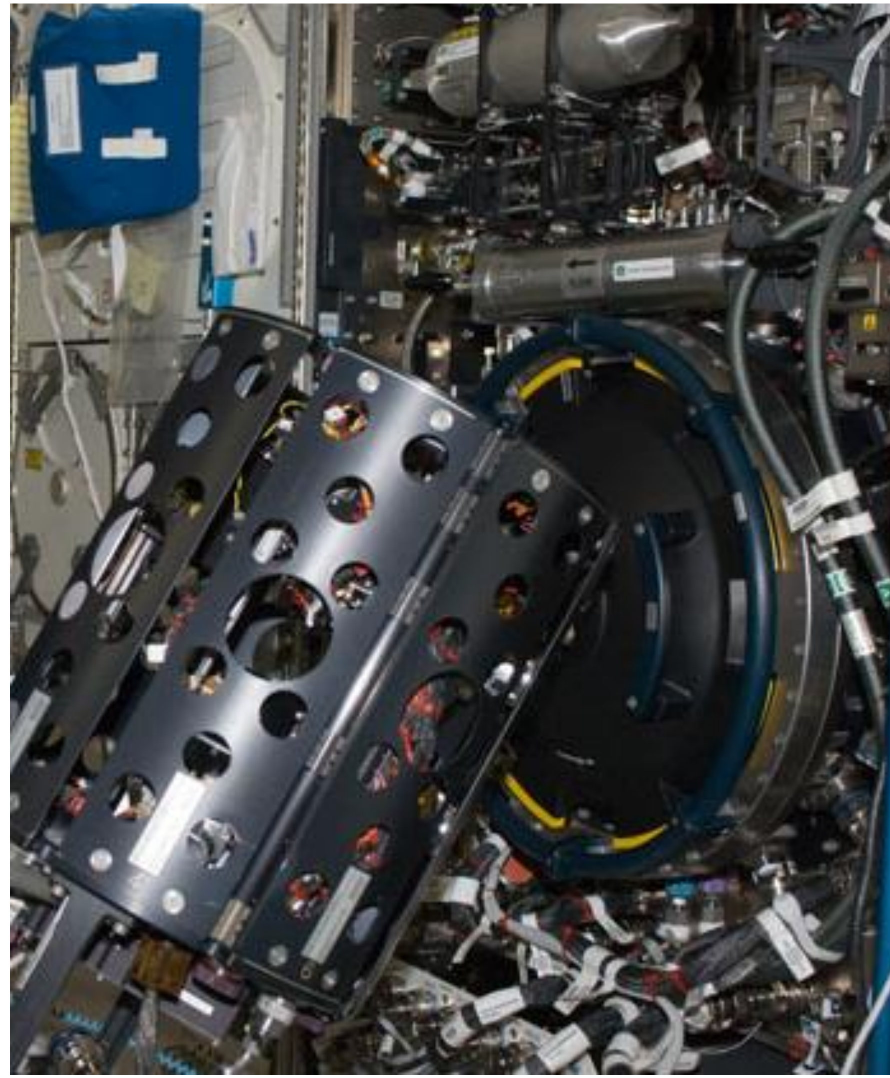
GigE	Gigabit Ethernet (color camera)
HiBMs	High Bit-depth Multi-spectral camera
IPSU	Image Processing and Storage Unit
LLL-UV	Low Light Level Ultraviolet camera
PMT	Photomultiplier Tube module
R	Radiometers

Additional Diagnostics

- Heat flux (BRE burners, on & off axis)
- Temperature
  - Burner surface (with 0-2 TCs)
  - Far-field gas phase
    - 2 fixed thermocouples (TCs)
    - rake with 4 TCs is crew removable or swappable for different TC positions
- Ion current (electric field tests only)
- Pre- & post-test gas composition
  - via gas chromatograph
  - e.g., CO, CO2, CH4, C2H2, C2H4, N2, O2



Thermocouple rake and 2 fixed thermocouples



Monitoring Measurements

- Chamber pressure
- Gas flow rates
- Burner pressure differential
  - *for porous burners*
- Electrical potential
  - *for tests with the electric field*
- Acceleration
  - *i.e., effective gravity*

These measurements are required to verify boundary & initial conditions and thus enable modeling and analysis.

Michael Barratt with MDCA in CIR

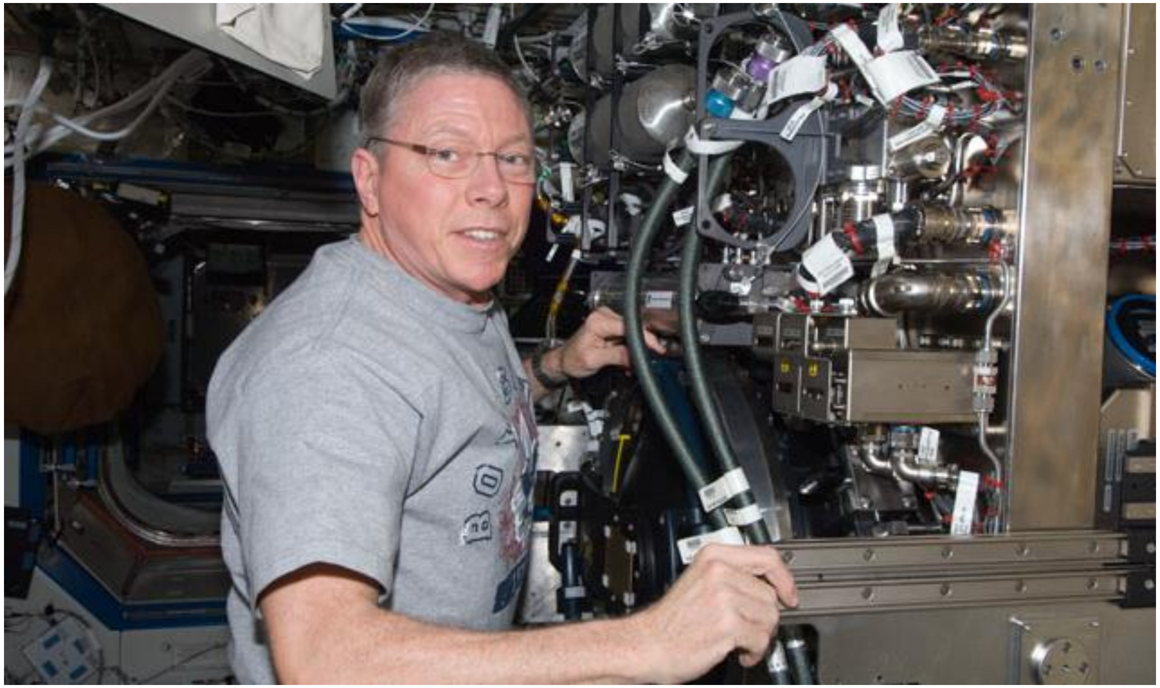
Nominal Operational Sequence

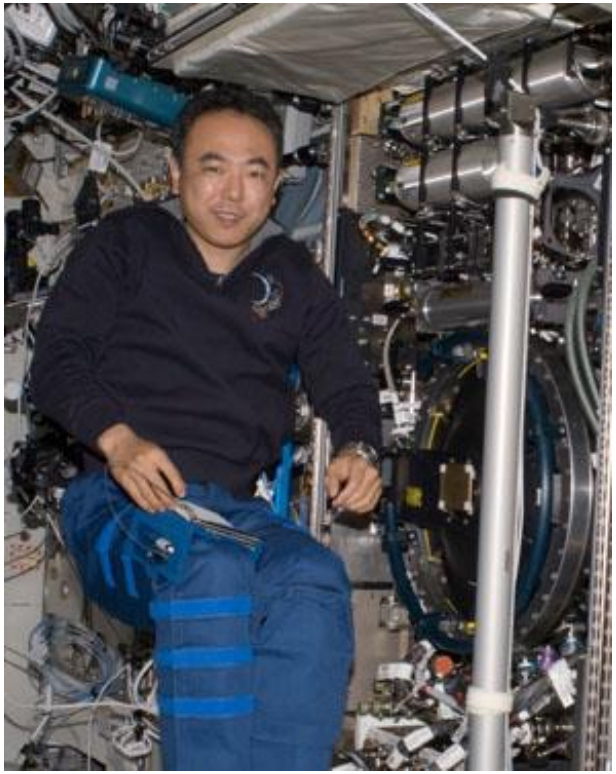
- **Flow > Ignite > Measure > Extinguish**
  - Initiate burner flows at ignition condition
  - Ignite flame
    - Wait for flame to stabilize
  - If needed, adjust flow(s) to initial test condition
    - Wait for flame to stabilize
  - If desired:
    - increase or decrease burner flow(s)
      - to vary flow/velocity or concentration
    - activate and adjust electric field
    - translate TFP array
  - Stop burner flows
    - per extinction detection, test duration, etc.
- **Ops control can be automated or "manual"**
  - Ground control, **not** astronaut operated

Nicole Stott with CIR

ACME Status

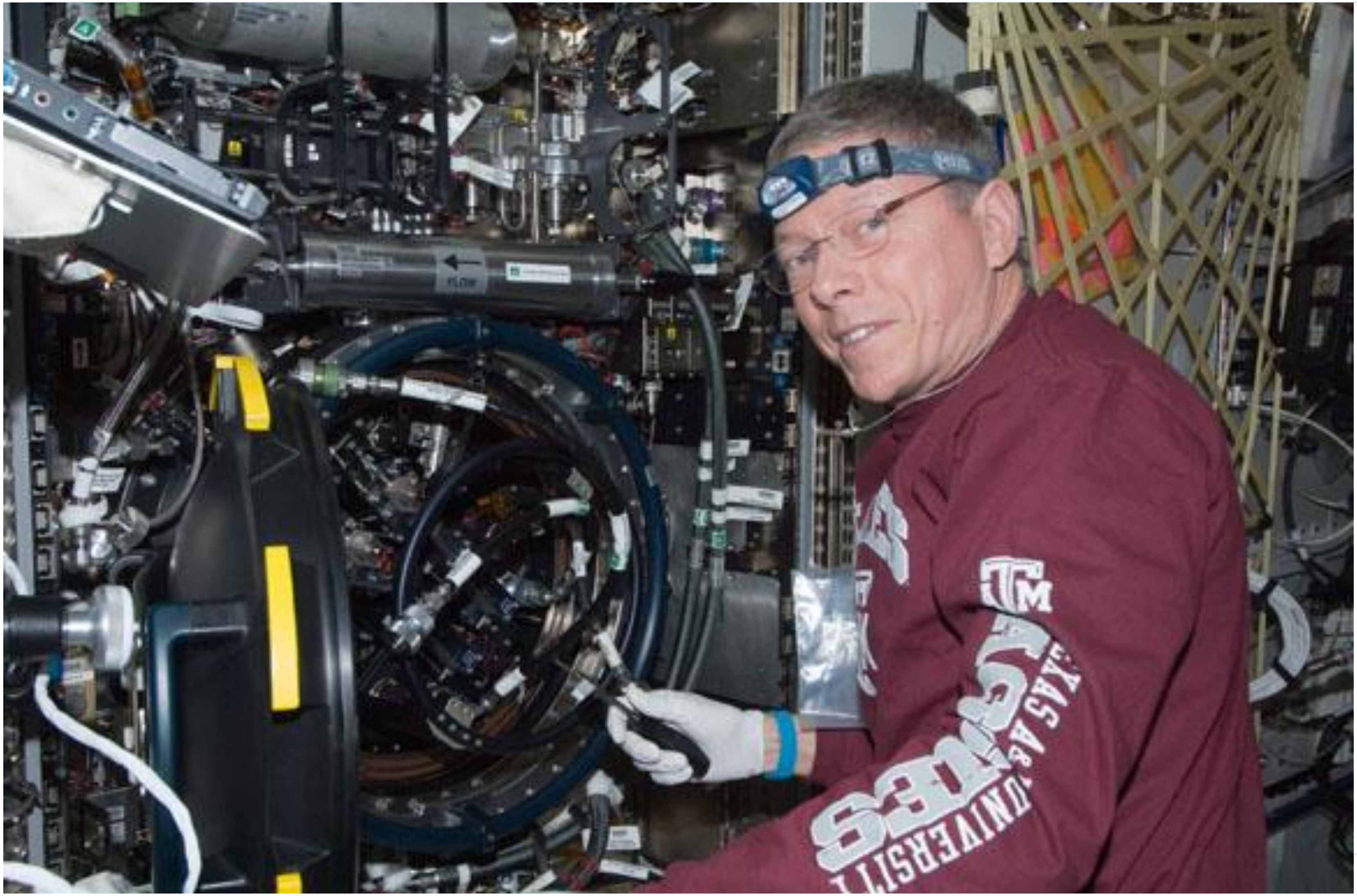
- **Schedule**
  - 2013 Critical Design Review (CDR)
  - 2014 (*now*) completion of detailed design for spaceflight hardware
    assembly of engineering models
    fabrication of spaceflight hardware
  - 2016-2019 ISS ops





Mike Fossum with CIR (left), Satoshi Furukawa with CIR (right)

Questions?



MICROGRAVITY

Mike Fossum with MDCA in CIR

Acknowledgements

- **Investigators (*7 universities and NASA Glenn*)**
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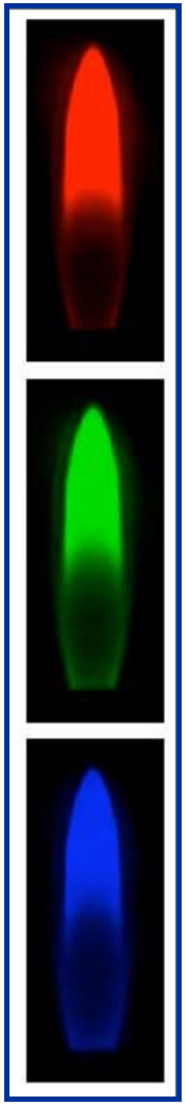
ZIN Technologies, Inc.

BACKUP

Why Study Combustion?

- **Energy**
  - While we might associate fire with the Stone Age, we still make extensive use of combustion in our daily lives.
    - Electricity – about 70% in the U.S. from combustion
    - Heating of buildings, water, food, and in manufacturing processes
    - Transportation
  - Our reliance on imported fuel contributes to our national trade deficit and affects our national security.
- **Environment**
  - Combustion is a source of greenhouse gases.
  - Soot contributes to global warming and is a health problem.
- **Fire Safety**



Given its pervasive use ***with annual U.S. fuel costs on the order of a trillion dollars*** **even small improvements in combustion technology can significantly reduce fuel needs and pollution production!**